

****Volume Title****

*ASP Conference Series, Vol. **Volume Number***

****Author****

© ****Copyright Year**** *Astronomical Society of the Pacific*

Abundance Patterns in S-type AGB stars : Setting Constraints on Nucleosynthesis and Stellar Evolution Models

Pieter Neyskens¹, Sophie Van Eck¹, Bertrand Plez², Stéphane Goriely¹,
Lionel Siess¹ and Alain Jorissen¹

¹*Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles,
CP 226, Boulevard du Triomphe, B-1050 Bruxelles, Belgium*

²*GRAAL, Université Montpellier-II, CNRS-UMR 5024,
Place Eugène Bataillon, F-34095 Montpellier, France*

Abstract. During the evolution on the AGB, S-type stars are the first objects to experience s-process nucleosynthesis and third dredge-ups, and therefore to exhibit s-process signatures in their atmospheres. Their significant mass loss rates (10^{-7} to 10^{-6} M_{\odot} /year) make them major contributors to the AGB nucleosynthesis yields at solar metallicity. Precise abundance determinations in S stars are of the utmost importance for constraining e.g. the third dredge-up luminosity and efficiency (which has been only crudely parameterized in all current nucleosynthetic models so far). Here, dedicated S-star model atmospheres are used to determine precise abundances of key s-process elements, and to set constraints on nucleosynthesis and stellar evolution models. A special interest is paid to technetium, an element with no stable isotopes (⁹⁹Tc, the only isotope produced by the s-process in AGB stars, has a half-life of 2.1×10^5 years). Its detection is considered as the best signature that the star effectively populates the thermally-pulsing AGB phase of evolution. The derived Tc/Zr abundances are compared, as a function of the derived [Zr/Fe] overabundances, with AGB stellar model predictions. The [Zr/Fe] overabundances are in good agreement with the model predictions, while the Tc/Zr abundances are slightly overpredicted. This discrepancy can help to set better constraints on nucleosynthesis and stellar evolution models of AGB stars.

1. Introduction : S-type stars and the role of technetium

Based on their spectra, late-type stars are classified in three main groups: M, S and C stars. These groups differ in their surface chemical composition. Spectra of M stars are characterized by strong TiO absorption bands, while absorption bands of C₂ and other carbon-rich molecules appear in C star spectra. Stars showing absorption bands of ZrO (in addition to TiO absorption bands) are classified as S. The presence of ZrO presumes that S stars are located on the thermally-pulsing asymptotic giant branch (TPAGB), where the repeated occurrence of thermal pulses and third dredge-ups (3DUP) permits carbon and s-elements to be synthesized and brought to the stellar surface (Van Eck et al. 2001). Therefore S stars are believed to be transition objects between oxygen-rich M and carbon-rich C stars (Iben & Renzini 1983).

The presence of technetium (Tc, Z=43, an element with no stable isotope) in some S-star spectra (Merrill 1952) has led to a dichotomy among the S stars: *intrinsic* S stars exhibit Tc lines in their spectrum, while *extrinsic* S stars lack Tc absorption lines. The

laboratory half-life of ^{99}Tc (the isotope produced by the s-process in AGB stars) is 2.1×10^5 years, which is of the order of the time spent by low- and intermediate-mass stars on the TPAGB. This implies that *intrinsic* S stars are genuine TPAGB stars in contrast to *extrinsic* S stars. *Extrinsic* S stars did not produce their heavy elements themselves, but accreted them in the past from a close-by, now extinguished, companion TPAGB star (Van Eck & Jorissen 1999). Hence, *extrinsic* S stars are low-luminosity giant stars belonging to a binary system (Van Eck & Jorissen 1999, 2000).

Today, one of the major uncertainties in the AGB stellar evolution models has to deal with the s-process neutron source. Observations and models hint $^{13}\text{C}(\alpha, n)^{16}\text{O}$, instead of $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$, as being the dominant neutron source in low-mass AGB stars (Smith & Lambert 1986; Goriely & Mowlavi 2000). The efficiency of the ^{13}C neutron source depends on the amount of protons mixed down from the H-rich envelope into the C-rich intershell [Partial Mixing, PM, which triggers the chain $^{12}\text{C}(\text{p}, \gamma)^{13}\text{N}(\beta)^{13}\text{C}$]. Large uncertainties exist on the depth and on the formation of the ^{13}C pocket. Different mechanisms like convective overshooting, rotation and gravity waves have been proposed (Freytag et al. 1996; Siess et al. 2004; Denissenkov & Tout 2003). Details about the 3DUP are also badly known due to our lack of knowledge about convective mixing mechanisms in (AGB) stars. Furthermore, AGB modelling uncertainties do also arise from reaction rates uncertainties.

A detailed abundance analysis of Tc, Zr and Fe is able to set better constraints on the large uncertainties of the mixing and nucleosynthetic processes inside AGB stars since different assumptions on the PM, the s-process nucleosynthesis and the 3DUP will lead to different abundance predictions of carbon and s-elements (Goriely & Mowlavi 2000). The surface enrichment in Tc is, in contrast to other s-elements, hampered by its radioactive decay. This property gives rise to an almost time-independent surface abundance of Tc during the ascent of the AGB, while the abundance of all the other s-elements increases progressively (Van Eck et al. 2001). However, it is a hard task to derive accurate chemical abundances in AGB stars, especially in S stars. The thermal structure of S stars is, in contrast to M stars, also influenced by the non-solar C/O ratio and s-process abundances. The use of equivalent widths to derive abundances of individual elements in S stars involves large errors due to the strong molecular blending, which makes it hard to access the continuum flux. A higher precision in abundance determinations could be obtained by spectrum synthesis from a S-star model atmosphere.

S-star MARCS model atmospheres were computed with the latest version of the MARCS code for late-type stars (Gustafsson et al. 2008). The S-star model atmospheres are covering a large set of atmospheric parameters (see Van Eck et al. this volume). The resulting synthetic spectra are compared with high-resolution observed spectra to obtain abundances of Tc, Zr and Fe for 7 *intrinsic* S stars from the sample of 205 Henize S stars (Henize 1960) (This sample contains all *intrinsic* and *extrinsic* S stars with $R \leq 10.5$ and $\delta \leq -25^\circ$).

2. Observational data for the Henize S stars and S-star MARCS model atmospheres

Optical low-resolution Boller & Chivens spectra ($\Delta\lambda = 3 \text{ \AA}$, 4400 \AA -8200 \AA) were obtained for a large fraction of the Henize S stars, in January 1997 at La Silla with the 1.52m ESO telescope. High-resolution Coudé Echelle spectra ($\Delta\lambda \approx 0.08 \text{ \AA}$, 4220 \AA -4280 \AA) were also taken around that time with the 1.4m CAT telescope at ESO. The

high-resolution spectra are covering two Tc I lines: Tc I 4238.191 Å and Tc I 4262.270 Å. This implies that the presence or absence of Tc can be checked in a consistent way. Optical Geneva UVB photometry and infrared SAAO JHKL photometry (Catchpole, priv. comm.) are also available (Van Eck et al. 2000).

The extended grid of MARCS model atmospheres for S stars contains 3522 models for $2700 \text{ K} \leq T_{\text{eff}} \leq 4000 \text{ K}$ (steps of 100 K), $0.0 \leq \log g \leq 5.0$ (steps of 1.0), $[\text{Fe}/\text{H}] = 0.0$ and -0.5 , $\text{C}/\text{O} = 0.501, 0.751, 0.899, 0.925, 0.951, 0.971$ and 0.991 , and $[\text{s}/\text{Fe}] = 0.0, +1.0$ and $+2.0$ dex. These 1D models are constructed with the assumptions of homogeneous stationary layers, hydrostatic and local thermodynamic equilibrium, and energy conservation by radiative and convective fluxes. The opacity sampling technique is used and different continuous and line opacities are taken into account. Properties of the MARCS model atmospheres for S stars and the resulting synthetic spectra are discussed elsewhere (Gustafsson et al. 2008; Van Eck et al. this volume).

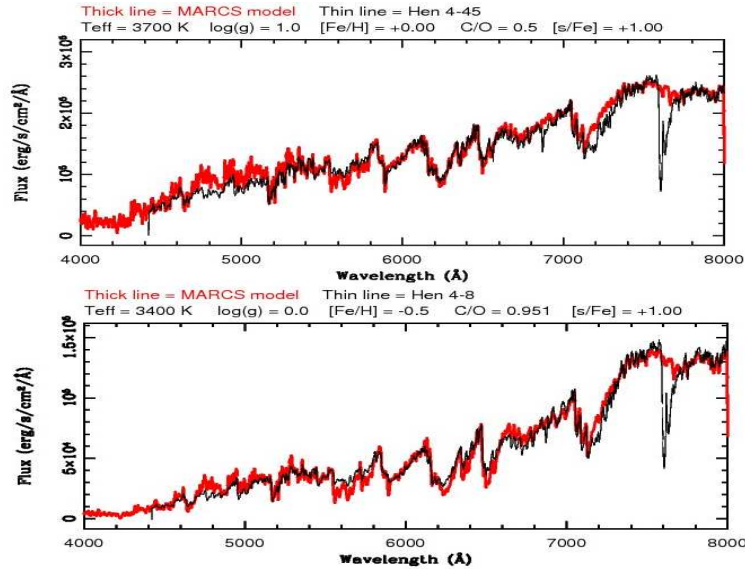


Figure 1. A comparison between the observed low-resolution optical spectrum (thin black line) and the selected synthetic spectrum (thick red line) for Henize 4-45 (top) and Henize 4-8 (bottom). The atmospheric parameters of the synthetic spectra are given at the top of each panel. The 7600 Å feature is from telluric O₂.

3. Deriving abundances of intrinsic S stars

To derive abundances in S stars, from the comparison between optical high-resolution observed spectra and synthetic spectra, one has first to find the atmospheric parameters. The estimate of the stellar parameters is based on the comparison between observed and synthetic colors (UBV & JHKL) and between observed and synthetic band-strengths (TiO, ZrO and NaD). More information about this so-called “best-model finding tool” is given in Sects. 3 and 4 of Van Eck et al. (this volume). The results are shown in Fig. 1. This figure compares (for two different Henize stars) dereddened observed low-resolution spectrum with the synthetic spectrum derived from the selected “best” S-star

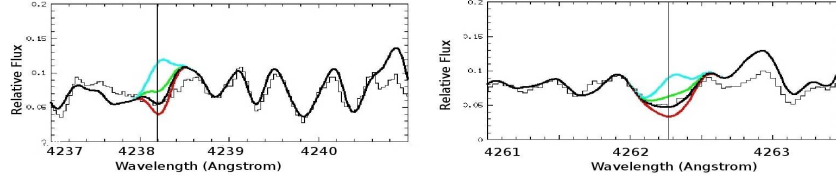


Figure 2. A synthesis of the two Tc lines (Tc I 4238.191 Å and Tc I 4262.270 Å) for 4 different Tc abundances (No Tc, $\log \varepsilon(\text{Tc}) = 0.0$, $\log \varepsilon(\text{Tc}) = 0.3$ and $\log \varepsilon(\text{Tc}) = 0.6$) compared with the high-resolution observation (thin line) of Hen 4-162.

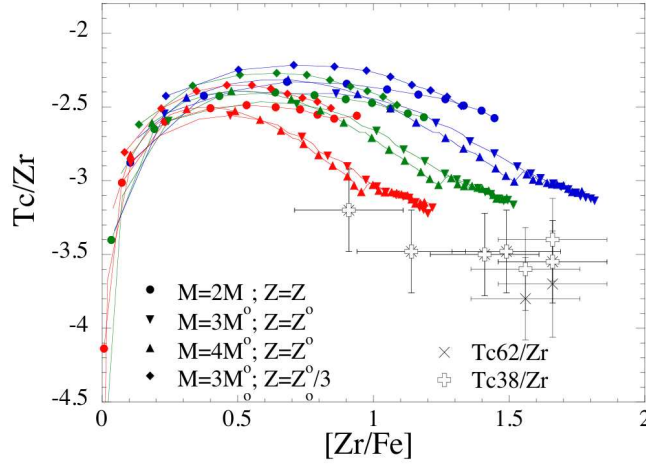


Figure 3. Comparison between observed and predicted Tc/Zr ratios as a function of the [Zr/Fe] overabundances. Four model stars with different masses and metallicities are considered ($M = 2, 3, 4 M_{\odot}$ at solar metallicity and $M = 3 M_{\odot}$ for $Z = Z_{\odot}/3$). For each star, the envelope s-process enrichment is calculated all along the AGB phase (the symbols correspond to the abundance ratio just after the third dredge-up) assuming 3 different values for the extent of the partial mixing zone λ_{pm} : for each star (i.e. given symbols), the leftmost curve corresponds to $\lambda_{pm}=0.05$, the rightmost to $\lambda_{pm}=0.20$ and the middle one to $\lambda_{pm}=0.10$. Observations are shown by the two cross types. Tc62 and Tc38 are the Tc abundances derived from the Tc I 4262.270 Å and Tc I 4238.191 Å lines respectively.

MARCS model. The dereddening of the observed spectra is based on Cardelli et al. (1989). Besides photometry, these visual comparisons serve as checks for the derived atmospheric parameters, since the stellar parameters largely influence the spectral shape and the strength of the TiO and ZrO bands.

Synthetic high-resolution spectra, based on the derived atmospheric parameters, are then compared with high-resolution observed spectra. This allows us to fine-tune the individual chemical abundances to obtain a good match between the observed and syn-

thetic spectra. In this way, abundances of Tc, Zr and Fe were obtained. Fig. 2 shows a fit of the two Tc I lines at 4238.191 Å and 4262.270 Å respectively.

4. Comparison between the derived abundances and the stellar evolution models

The final Tc/Zr abundances are shown in Fig. 3 as a function of the [Zr/Fe] overabundances. The observations are also compared in Fig. 3 with post-processing s-process calculations performed on 4 AGB models computed with the stellar evolution code STAREVOL (Siess 2007). The s-process model considered here corresponds to the partial mixing of protons into the C-rich region at the time of the third dredge-up, as described in detail in Goriely & Mowlavi (2000). The extent of the partial mixing zone is varied between 5% and 20% of the extent of the thermal pulse (λ_{pm} corresponds to the ratio of the mass of the partial mixing zone to the mass of the thermal pulse at its maximum extension), so that the s-process enrichment in the stellar envelope reaches values compatible with the observations, i.e about 1 to 2 dex enrichment for [Zr/Fe]. As can be seen in Fig. 3, the Tc/Zr ratio is systematically overpredicted. Different explanations for this discrepancy can be given, in particular the partial decay of Tc, either during longer interpulse phases (e.g in lower-mass stars) or during hotter thermal pulses (at $T=3 \times 10^8$ K, the ^{99}Tc half-life is reduced from 2×10^5 yr to about 9 yr). These new observations (complemented with Nb abundance determination) can provide strong constraints regarding the s-process in AGB stars. The present data will be further analyzed and interpreted in a forthcoming paper.

The derivation of S-star atmospheric parameters (T_{eff} , $\log g$, [Fe/H], C/O and [s/Fe]) and individual abundances, and the comparison with stellar evolution AGB models, will be done on a larger sample of S stars in the near future. The agreement between infrared synthetic spectra (constructed from the derived atmospheric parameters) and infrared observed spectra of S stars will also be tested.

Acknowledgments. P.N. is *Boursier F.R.I.A.*, Belgium. S.V.E., S.G. and L.S. are F.R.S.-F.N.R.S. research associates. This research has been supported by the *Communauté Française de Belgique - Actions de Recherche Concertées*.

References

- Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
- Denissenkov, P. A., & Tout, C. A. 2003, MNRAS, 340, 722
- Freytag, B., Ludwig, H., & Steffen, M. 1996, A&A, 313, 497
- Goriely, S., & Mowlavi, N. 2000, A&A, 362, 599
- Gustafsson, B., Edvardsson, B., Eriksson, K., Jørgensen, U. G., Nordlund, Å., & Plez, B. 2008, A&A, 486, 951
- Henize, K. G. 1960, AJ, 65, 491
- Iben, I., Jr., & Renzini, A. 1983, ARA&A, 21, 271
- Merrill, S. P. W. 1952, ApJ, 116, 21
- Siess, L. 2007, A&A, 476, 893
- Siess, L., Goriely, S., & Langer, N. 2004, A&A, 415, 1089
- Smith, V. V., & Lambert, D. L. 1986, ApJ, 311, 843
- Van Eck, S., & Jorissen, A. 1999, A&A, 345, 127
- 2000, A&A, 360, 196
- Van Eck, S., Jorissen, A., Goriely, S., & Plez, B. 2001, Nuclear Physics A, 688, 45
- Van Eck, S., Jorissen, A., Udry, S., Mayor, M., Burki, G., Burnet, M., & Catchpole, R. 2000, A&AS, 145, 51